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Geology, Groundwater Chemistry and Management of the Dakota Aquifer in Nebraska

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Introduction

The Dakota aquifer of the central Great Plains is a key secondary aquifer in many parts of Nebraska. It is an important source of water for municipal, industrial and domestic supplies in an area that runs from the northern to the eastern and southeastern parts of the state. While the regional groundwater flow can be characterized generally as moving northeast from the Rocky Mountains to the Missouri River, locally the flow systems are hydrologically complex.

One example of its value, its limitations and its complexity comes from the history of water development in the state capitol. For about the first 50 years of Lincoln's settlement, the aquifer kept the city reasonably well supplied with good quality water. However, as early as the late 1920s, Lincoln was withdrawing enough Dakota water to induce saline water encroaching on the freshwater supplies. This complication meant that relatively recent recharge, which had kept out or diluted saline water, was being used more rapidly than it was being replaced and saline water supplies were being pumped. Lincoln had to move its major well field to the sand-and-gravel sediments of the lower Platte River valley. Wells within the city still provide supplemental water during peak usage periods, but if pumped too much, will yield saline water.

With increasing developmental pressures, particularly in eastern Nebraska, natural-resource agencies need more detailed information on these flow systems in order to develop water-management strategies and policies. Based on our studies, the most significant conclusion related to management of the Dakota is that each region requires its own strategy, one tailored to the nature of the aquifer and water in that region.

Challenges

Much is known about the Dakota in the Lincoln area, but the main factor complicating more intensive study of the aquifer in other parts of the state has been a lack of monitoring wells and other monitoring equipment. Using the distinctive water chemistry of the Dakota and archived water-quality information to our advantage and applying geochemical modeling and isotope analysis, we have acquired an idea of what the water "has seen" as it has moved through the flow system. The chemistry, in effect, provides a record of the history of the water that, in turn, can be used to provide constraints for management.

Regional Hydrogeologic Setting

The Dakota (Great Plains) aquifer and its water-bearing equivalents comprise one of the most extensive aquifer systems in North America, extending from the Arctic Circle to New Mexico and from the Rocky Mountain front to the eastern Great Plains of Minnesota and Iowa (fig. 1). Over most of its extent in the central Great Plains, younger Cretaceous chalks and shales (fig. 2) confine the Dakota aquifer. These units have been eroded along the elevated Rocky Mountain front and in the outcrop/subcrop belt in the eastern Great Plains (fig. 3). We focus on northeastern, eastern and southeastern Nebraska (fig. 1), where the Dakota is used as a primary or secondary source of water.

In the central Great Plains, the Dakota aquifer consists primarily of the Dakota Formation, which occurs in parts of Nebraska, South Dakota, North Dakota, Kansas, Iowa and Minnesota, according to Witzke and Ludvigson (1994). For eastern Nebraska, they have defined a general sequence for the formation that includes a lower sandstone-dominated Nishnabotna Member and an upper mudstone-dominated Woodbury Member. The Woodbury Member is recognized in northeastern and east-central Nebraska and is the primary hydrostratigraphic unit (water-bearing layer). Its thickness ranges from 15 to 70 meters (9 to 42 feet) in the east to about

Rod Root, a CSD technician working on the geology of the Dakota, examines a Dakota Sandstone outcrop at Mahoney State Park near Ashland.

Photo by Matt Joeckel, CSD

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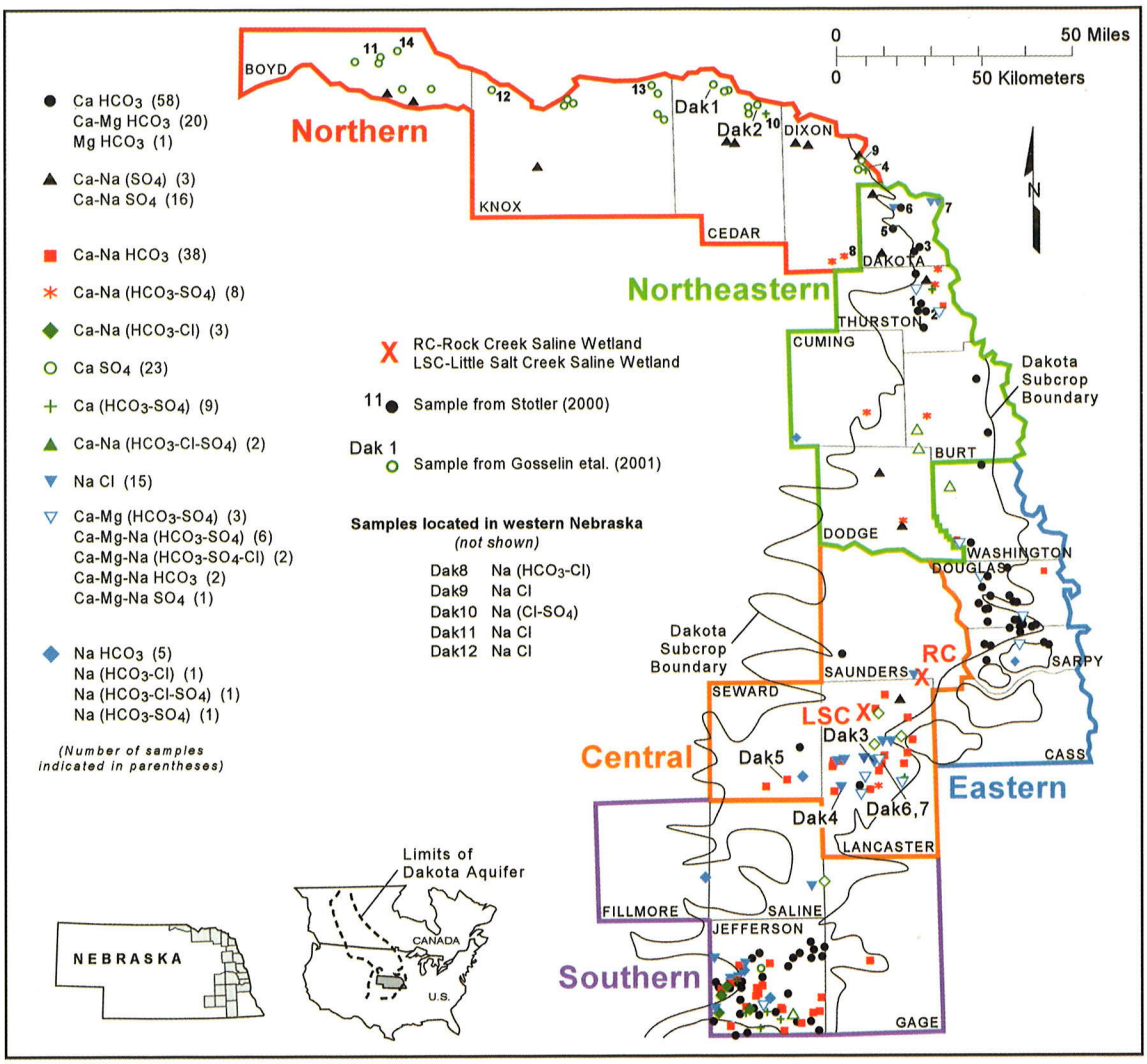

Fig. 1. Sample locations and groundwater chemistry types across eastern Nebraska by region.

120 meters (72 feet) westward. Although Woodbury strata are dominated by mudstones, shales, and siltstone, very fine- to fine-grained, channel-shaped sandstone bodies are present ranging in thickness from less than 1 meter up to 25 meters (0.6 to 15 feet).

In east-central Nebraska, especially between Omaha and Lincoln, the Woodbury Member is not recognizable, and the continuous sandstone bodies of the Nishnabotna Member are the primary hydrostratigraphic unit. The thickness of the Nishnabotna in Nebraska is not well known but is thought to be highly variable and probably less than 75 meters (45 feet) thick. Farther west and south, the Nishnabotna and Woodbury members cannot be differentiated. Veatch (1969) said that the sandstone bodies are geometrically complex and discontinuously interbedded with shales in southeastern Nebraska.

The Dakota Formation is completely or partially overlain by the Great Plains confining system (Jorgensen and others, 1993), composed predominantly of Upper Cretaceous marine shales that include the Graneros Shale, Greenhorn Limestone, the Carlisle Shale, Niobrara Formation and the Pierre Shale. In eastern Nebraska, where the confining unit has been eroded the Dakota Formation is overlain by Quaternary deposits consisting of glacial till and loess.

In the northern part of Nebraska, the Dakota Formation is underlain primarily by Lower Paleozoic dolomite, with the exception of northern Knox County, where it rests on the Precambrian Sioux Quartzite. From northern Burt and Cuming counties down into the middle of Lancaster and southern Seward counties, the Dakota rests on Pennsylvanian rocks. The Pennsylvanian rocks consist of alternating units of marine limestones and shales. Southward from Lancaster County into Kansas, the Dakota rests on Permian and Jurassic sedimentary rocks that are predominantly limestones and shales.

Origins and Chemistry of the Groundwater

We discuss our analysis of the water's origins and chemistry by geographic regions of Nebraska: Northern, Northeastern, Eastern, Central, Southern and Western. The location of the water samples are shown on figure 1 in the context of their water classification. Average values for the major water types are given in table 1.

The composition of the Dakota waters is complex and, in some instances can be quite mineralized, as outlined in the example concerning Lincoln. The extent to which a water is mineralized mostly affects the water's taste and its effect on plumbing systems, not human health. The overall mineralization of the water can be characterized by the total dissolved solids (TDS). The U.S. Environmental Protection Agency does not have a specific regulatory limit for TDS, but it has recommended a general limit of 500 milligrams per liter (mg/l) TDS

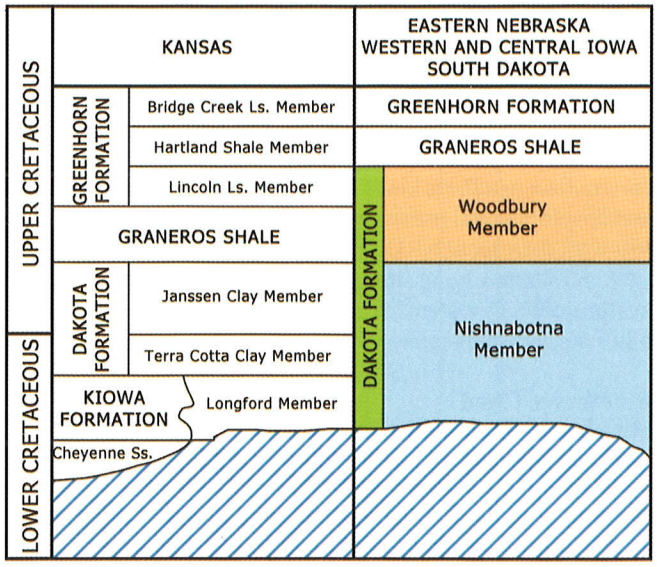

Fig. 2. Stratigraphic column of Upper and Lower Cretaceous units in central Great Plains.

based largely on aesthetic (look and taste) considerations. Water applied to crops is also generally suitable if the TDS concentration is 500 mg/l or less. With adequate drainage and leaching, concentrations between 500 and 1,500 mg/l are not considered harmful to most crops.

The Central and Southern areas – evolution and source of saline (NaCl) waters

Groundwater from the Dakota Formation in Lancaster, Saunders, and Seward counties are predominantly water types containing calcium-sodium bicarbonate (Ca-Na-HCO_3) and sodium-chloride (NaCl – the same chemical composition as table salt). Other water types in this area include calcium-sodium bicarbonate-chloride, or Ca-Na (HCO_3-Cl), calcium-magnesium bicarbonate-sulfate, or Ca-Mg (HCO_3-SO_4), and calcium-sodium bicarbonate-sulfate chloride, or Ca-Na (HCO_3-SO_4)±Cl. The Ca-Na-HCO_3 waters are predominantly to the east and south of Lincoln, as well as to the west. These waters have TDS that are generally less than 400 mg/l but range from 300 to 500 mg/l.

Groundwater from the Dakota Formation in Fillmore, Saline, Gage and Jefferson counties is predominantly Ca-HCO_3, Ca-Na HCO_3 and NaCl type waters. The NaCl waters occur near the boundary between the Dakota Formation and overlying confining shales. The TDS of the $CaHCO_3$ waters range from 315 to 530 mg/l, with most of the values being less than 425 mg/l. The majority of the Ca-Na HCO_3 waters have TDS less than 450 mg/l, but have a range from 200 to 1,060 mg/l.

The sodium-chloride-type waters have TDS that range from 2,100 to 13,000 mg/l. Even TDS of up to 44,000 mg/l have been reported. NaCl or saline waters occur in the vicinity of Lincoln, as well as near the contact between the Greenhorn-Graneros formations and the Dakota Formation in western Jefferson County. Groundwater can only evolve to a chloride-rich brine if it encounters highly soluble chloride-containing minerals, typically associated with evaporative deposits (evaporites). It is unlikely that the right conditions existed for evaporites to form during the deposition of the Dakota Formation (Witzke and Ludvigsen, 1994), because these predominantly sandstone deposits were formed in environments dominated by rivers and streams near the margins of a great seaway. Evaporites usually do not form in these environments. Therefore, the saline water could not form as the result of simple interaction between Dakota Formation rocks and the groundwater that flowed through it, as earlier researchers have suggested. Instead, the saline waters have most likely evolved from the dissolving (dissolution) of halite obtained from some other geologic unit.

The Na/Cl ratios are consistent with the dissolution of halite, as well as the dilution or evaporation of seawater (Fig. 4). The majority of NaCl waters have Na and Cl concentrations that are similar to modern seawater or fall along a line that represents the dilution of seawater. Isotope data also suggest that these saline waters are similar to modern meteoric (precipitation-derived) water and eliminate evaporation as a major process in producing the salinity.

In 1887, a 751-meter (2,463 feet) exploratory well was drilled in what is now west Lincoln. Three saline zones were identified during the drilling (Condra and Reed, 1939). Zone 1 was in lower part of the Dakota. The other two zones were in formations in the Pennsylvanian Shawnee Group (Lecompton-Oread formations) and the Kansas City Group (Drum Formation). Waters from these zones flowed to the surface under artesian conditions (pressure resulting from confinement allowing for possible upward movement of water). The compositions of Pennsylvanian-derived NaCl waters and those in the Dakota are compared on Figure 4. The majority of the Dakota NaCl waters from Lancaster County have Na and Cl concentrations similar to the saline groundwater in the Shawnee Group that was obtained from a well near the Lincoln post office (Figure 4). In addition, other characteristic ratios for the saline waters in the Dakota from Lancaster County compare well with those found in the Pennsylvanian waters, in particular, the Ca/(HCO_3+SO_4), Na/Cl and the SO_4/Cl ratios.

Condra and Reed (1939) indicated that the salt water from the Pennsylvanian zones could not be the source of the saline waters in the Dakota because these zones were separated from

Fig. 3. Generalized east-west cross section of Dakota aquifer, Permian sandstone and regional and local flow patterns.

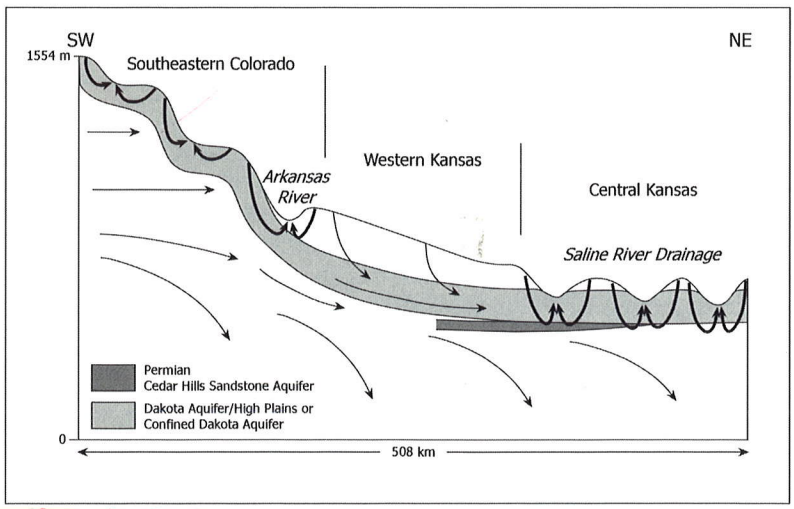

Fig. 3 is modified from: Clark, J.F., Davisson, M.L., Hudson, G.B., and Macfarlane, P.A., 1998. Noble gases, stable isotopes, and radiocarbon as tracers of flow in the Dakota aquifer, Colorado and Kansas. J. Hydrol. 211, 151-167.

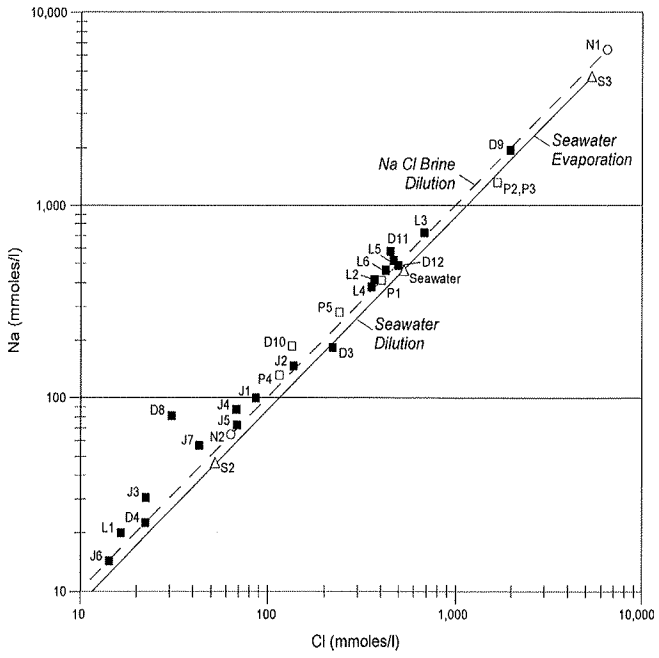

Fig. 4. Na versus Cl for groundwater used in this study. Open triangles: related to sea water and its evaporation (S3) or dilution (S4). Open circles: related to dissolution of halite (N1) and its dilution. Open squares: groundwater samples from the Pennsylvanian limestones. Closed squares: groundwater samples from the Dakota Formation in Jefferson County (J), Lancaster County (L) and Table 1 (D).

the Dakota by "thick, impervious zones" that do not allow saline fluids to move upward. However, in other parts of the Dakota aquifer, specifically in South Dakota, other workers have indicated that where pre-Cretaceous limestones underlie the Dakota, they can be significant sources of water to this aquifer (Swenson, 1968; Bredehoeft and others, 1983). Moreover, in the South Dakota area, Kolm and Peter (1984) argue for vertical leakage within fracture zones. Even without fractures, significant amounts of water can move vertically through relatively low-conductivity layers because of the very large areas underlain by the Dakota (Swenson, 1968; Helgeson and others, 1984). Fractures and faults are common in the pre-Cretaceous rocks of eastern Nebraska. More specifically, there is an east-to-west trending structural feature, known as the Denton Arch (Burchett, 1982), that crosses the middle part of Lancaster County, so that pathways for the upward movement of water from older units are certainly feasible. Because of the potential for vertical movement and the documented artesian conditions, we believe the source of the saline waters is in the Pennsylvanian rocks.

The Na to Cl relationships (Figure 4) and the predominance of Na and Cl in the waters from the Pennsylvanian rocks strongly indicate that the salinity came from the dissolution of halite, followed by its dilution. Other chemical evidence from Sr isotopes and geochemical modeling support this conclusion. These chemical data are consistent with the geologic history of the Pennsylvanian rocks in Nebraska, in which salt beds were deposited along with limestones and a variety of other marine facies as seaways became more restricted in western Nebraska (Carlson, 1993).

Although the NaCl waters in Jefferson County have Na/Cl ratios (Fig. 4) consistent with halite dissolution, the geologic source of the saline water is probably different from that in the Lincoln area, where the Dakota is underlain by Pennsylvanian formations. Jefferson County is underlain by Permian strata. The Cimmaron Series of Permian age, which has halite deposits, occurs just west of the area where NaCl-type waters have been observed. We think that these saline waters are a northward extension of the saline waters in Kansas that have a Permian source (Whittemore and others, 1994).

The Eastern Area – evolution of $CaHCO_3$ and Ca-$MgHCO_3$ waters

Waters from the eastern area – Washington, Douglas and Sarpy counties – are almost exclusively $CaHCO_3$ and Ca-$MgHCO_3$ waters having TDS less than 500 mg/l. The Nishnabotna member of the Dakota Formation is the predominant unit of groundwater geology in this area. These types of waters are produced by the weathering of silicate minerals in the Nishnabotna member. This interpretation is consistent with a variety of geochemical indicators and supported by geochemical modeling. Most important for management *(see management section below)*, the low TDS in these bicarbonate-dominated waters is consistent with these groundwaters having been recharged relatively recently by local precipitation.

The Northern Area – evolution of $CaSO_4$ and Ca-Na SO_4 waters

In northern Nebraska (Boyd, Knox, Cedar and Dixon counties), calcium sulfate ($CaSO_4$)-type waters predominate along with some calcium-sodium sulfate (Ca-Na SO_4) waters. Both of these water types are associated with the Dakota where it is overlain by confining shale units. The Ca-Na waters generally occur to the south of the Ca-dominated waters. The average TDS in the $CaSO_4$ and Ca-Na SO_4-type waters are 1,100 and 1,400 milligrams per liter (mg/l), respectively.

In northern Nebraska, the $CaSO_4$ and Ca-Na SO_4 waters occur where the Dakota is overlain by confining shale units. While these waters appear to have an origin as local precipitation, our stable isotope data suggest that the average yearly atmospheric temperatures during recharge were potentially 15°C (59° F) colder than current conditions. The generally high TDS of these water along with reconnaissance carbon dating suggests residence times on the order of thousands to tens of thousands of years. The source of these older waters may have been in eastern Nebraska during a colder climate associated with glaciation. An alternative idea is that they have migrated long distances from a source in western South Dakota. We are currently evaluating both these scenarios.

The Ca-Na SO_4 waters are probably $CaSO_4$ waters that have evolved to more sodium-rich compositions through the interaction with Na-bearing clays. The source of the sodium has not been specifically investigated, but the occurrence of saline (NaCl) brines having TDS greater than 10,000 mg/l to the south suggest that a source of sodium was likely available in the past.

The Northeastern Area – mixed water types

Groundwaters in Dakota and Thurston counties are predominantly Ca-Na-SO_4, Ca-Na (HCO_3-SO_4), and Ca-Mg-Na

Water Type	No. of Samples	Major Ions (mg/l -- except B and Fe, which are in micrograms per liter)													Total Dissolved Solids (mg/l)
		Temp °C	pH	Na	K	Ca	Mg	Cl	H-CO_3	SO_4	F	Si-O_2	B	Fe	
$CaSO_4$	16	17	7.4	59	17	220	40	55	157	624	1.5	11	229	2490	1,110
Ca-Na SO_4	16	16	7.4	157	27	210	47	82	218	753	2.1	8.9	581	3887	1,400
Ca- and Ca-Mg HCO_3	73	14	7.3	25	4.1	91	17	8.9	358	39	0.4	27	139	862	380
NaCl	13	14	7.6	4612	18	152	64	6557	430	885	1.2	16	1592	1529	12,500
Ca-Na HCO_3	36	13	7.1	60	5	77	13	32	310	65	0.4	28	243	1114	430
Others	38														
Total	192														

Table 1. Average major ion concentrations for water-types from the Dakota Formation in eastern Nebraska. Values for F, SiO_2, B and Fe were not available for all samples.

(HCO_3-SO_4)±Cl waters and are associated with the subcrop (underground) contact between the Dakota Formation and overlying Cretaceous shales. In southern Thurston County and eastern Burt County, $CaHCO_3$ waters become prevalent. Ca-Na-SO_4 and Ca-Na (HCO_3-SO_4) waters occur in Cuming, Dodge and western Burt counties. TDS in Ca-Na SO_4 waters range from 1,200 to nearly 1,900 mg/l. Ca-Na (HCO_3-SO_4) waters have TDS that range from 640 to 1,120 mg/l. Ca-HCO_3 and Ca-Mg-Na (HCO_3-SO_4)±Cl waters have TDS generally less than 500 mg/l.

The Ca-Na SO_4 waters occur where the Dakota is confined by the Cretaceous Carlile and Greenhorn-Graneros formations. These waters also occur in Dodge County. The Ca-Mg-Na (HCO_3-SO_4±Cl) and Ca-Na or Ca (HCO_3-SO_4) waters are associated with the contact between the Dakota and the Graneros-Greenhorn formations, primarily in Dakota and Thurston counties. Ca HCO_3 waters occur in areas where the Dakota is overlain by Pleistocene glacial till and/or loess. The complex distribution of water types is likely related to the transition of the Dakota from a predominantly confined to an unconfined aquifer. Research indicates that, as a result of thinning and erosional down-cutting through the confining units overlying the Dakota aquifer, there are variable degrees of recharge through the confining units and the establishment of local flow systems (see Macfarlane, 1995). In relative terms, where the confining unit is thin or has been removed, the Dakota can receive a relatively greater amount of local recharge that interacts with the water from the regionally derived, confined groundwater system. The amount of this recharge has significance for management *(see management section)*.

Compositionally, the recharge waters are likely to be $CaHCO_3$-type waters having relatively low TDS. Where the confining unit is thick and dense, the waters are Ca-NaSO_4 waters and represent the regional groundwater flow component. As the confining unit thins and the ability of groundwater to flow vertically is increased, local recharge can occur and the associated water chemistry becomes more variable. The chemical composition suggests interaction between the Ca-NaSO_4 waters at one end and the $CaHCO_3$ waters at the other end. The extent to which this mixing takes place is a function of dispersion and the time that the water has been in the aquifer. In addition, the interaction may have also been facilitated by changes in flow direction as a result of glaciation.

Management Strategies

A critical component to managing water resources is understanding the source of the groundwater extracted from a well. According to our analysis, there are three distinct sources for the groundwater in the Dakota. These include modern precipitation, NaCl brines from underlying formations, and older, colder sulfate-rich waters. Based on these three water sources and our current understanding of the geochemical evolution of the various water types in the Dakota, we suggest the following general management strategies.

Northern and Northeastern areas – $CaSO_4$- and Ca-Na SO_4-type waters

Management strategies should be most carefully tailored to specific aquifer conditions in the northern part of the state (Boyd, Knox, Cedar and Dixon counties). Isotope analyses suggest that some of this water may be very old, and, being under a thick confining layer, will not recharge quickly. The

groundwater extracted from wells in these areas is being removed from long-term aquifer storage. This water supply is not easily renewable.

Water in the northeastern part of the state (Dakota, Thurston, Cuming, Burt and Dodge counties), is of a mixed origin as the aquifer changes from a confined condition to unconfined farther south. The aquifer is largely recharged from the regional groundwater flow system where it is mostly confined and from the local system where it is mostly unconfined. The more recently recharged area has better potential for increased development. This potential is restricted by the provision that increased usage doesn't exceed the amount of input from local recharge and lead to mining of the aquifer. Where the aquifer is under varying degrees of confinement, changes in groundwater chemistry could be used to assess the extent to which a well is being influenced by water from the regional confined aquifer or local flow systems.

Eastern Area – Ca (±Mg) HCO_3 type waters

In the eastern part of the state (Washington, Douglas, Sarpy and Cass counties), the water has lower TDS than much of the Dakota. These waters occur where the Dakota aquifer is unconfined. Most of it is recharged locally and relatively recently by precipitation. This supply should be adequate for moderate development but may become a concern during drought.

The Central and Southeastern areas – mixed water types

In the central area (Saunders, Seward and Lancaster counties), and the southeastern area (Seward, Fillmore, Saline, Jefferson and Gage counties), the waters are a mixture of more modern, dilute recharge and those ranging from moderately to highly saline. These groundwaters most often reflect the interaction of two distinct water types, one of which is meteoric water ($CaHCO_3$-type) and the other is NaCl-type water. In Lancaster County, saline water has discharged at the surface in places, creating saline wetlands that originally attracted settlers who anticipated a thriving salt business. As indicated previously, the source of this salinity is probably below the Dakota in the Pennsylvanian rocks, and over-development could result in problems with saline water encroachment similar to those Lincoln faced early in its history.

In areas such as Lancaster County, where meteoric (local precipitation) recharge waters have likely displaced NaCl water downward, the vertical chemistry profile will be complex. There will be a progression from relatively fresh $CaHCO_3$-type water near the top to more saline, mixed groundwater types to NaCl waters at depth. If the fresher groundwater is extracted at a rate that cannot be maintained by recharge, then the water chemistry will change as the boundary between fresh and saline waters moves. In those areas where there is the possibility of saline water encroachment, chemical analysis of those wells can offer some idea when those kinds of problems might begin. If the water chemistry changes, then the pumping strategy should change. This monitoring is particularly important for supplies of smaller communities, and such supplies may be overextended during a drought.

Conclusion

Our main message is that "one size (or strategy) does not fit all" where Dakota groundwater management is concerned. This message also pertains to the classical, mostly unconfined Ogallala (or High Plains) aquifer. There are enough differences across the state that imposing a single management model will not work. Fortunately, the structure and distribution of the locally run natural resources districts (NRDs) are set up to accommodate just these kinds of variations in natural conditions and developmental pressures. Private landowners should consult with their local NRD or other experts for site-specific investigations involving siting of wells or geothermal-exchange heating-cooling systems, formation of rural water districts and other groundwater-related activities.

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